Sustainable Power for the Lunar Surface

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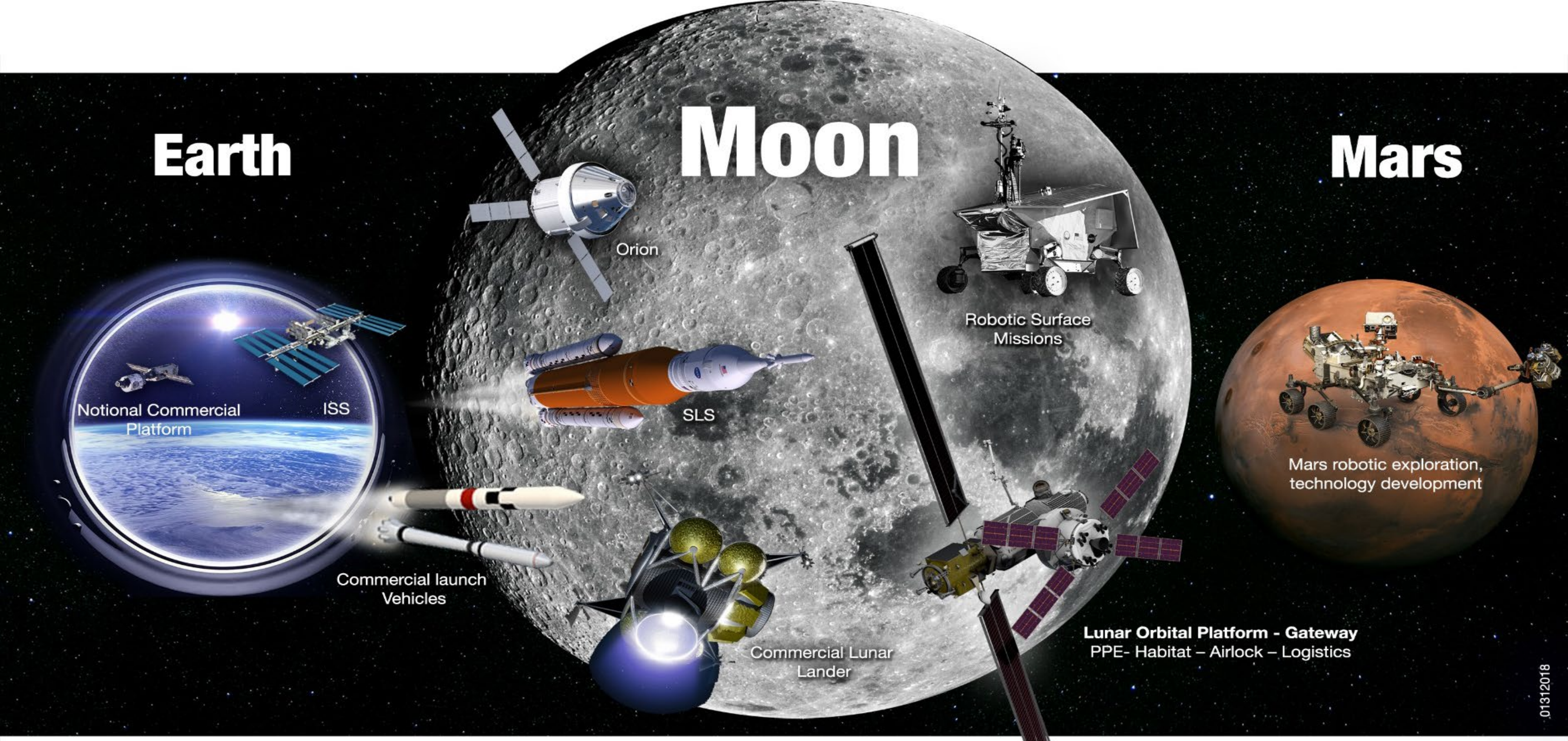
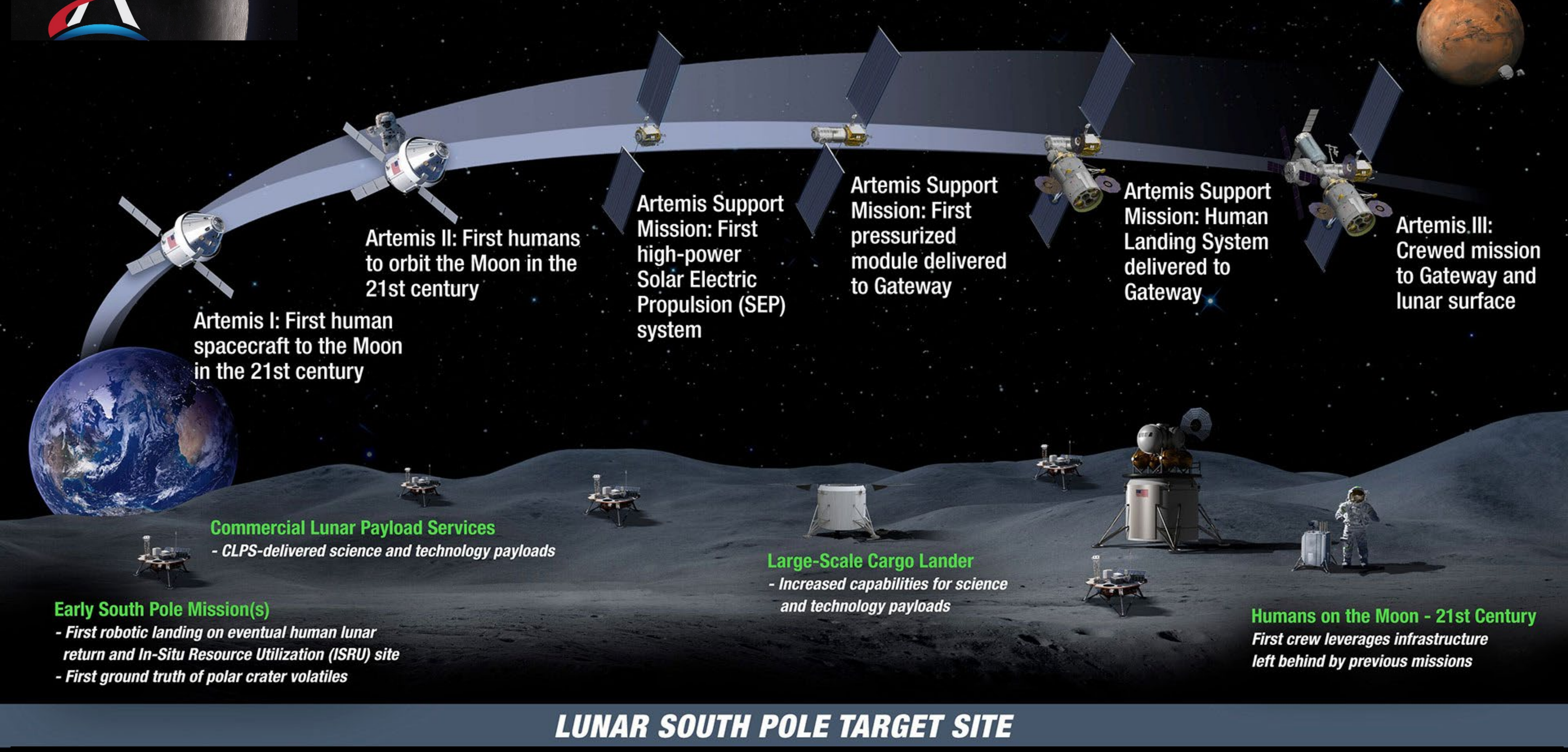


In LEO
Commercial & International partnerships

In Cislunar Space
A return to the moon for long-term exploration

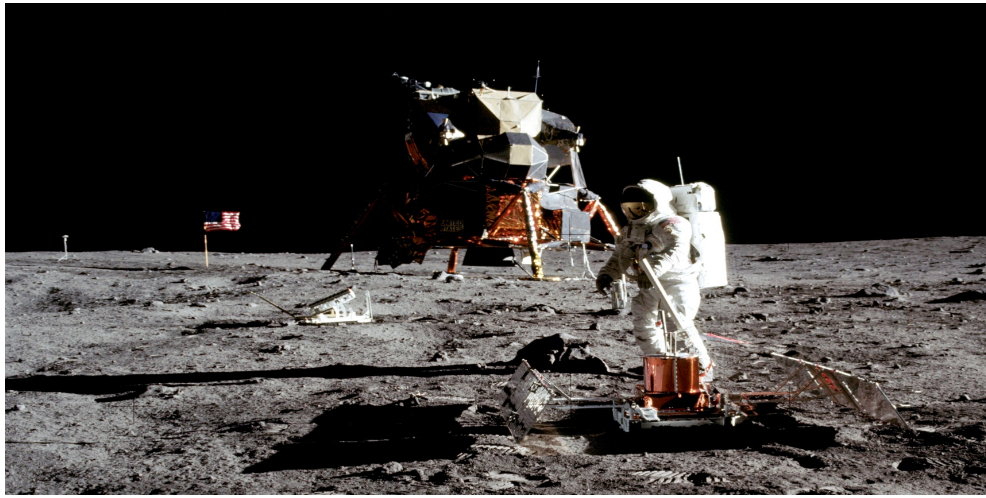
On Mars
Research to inform future crewed missions

NASA Artemis Plans

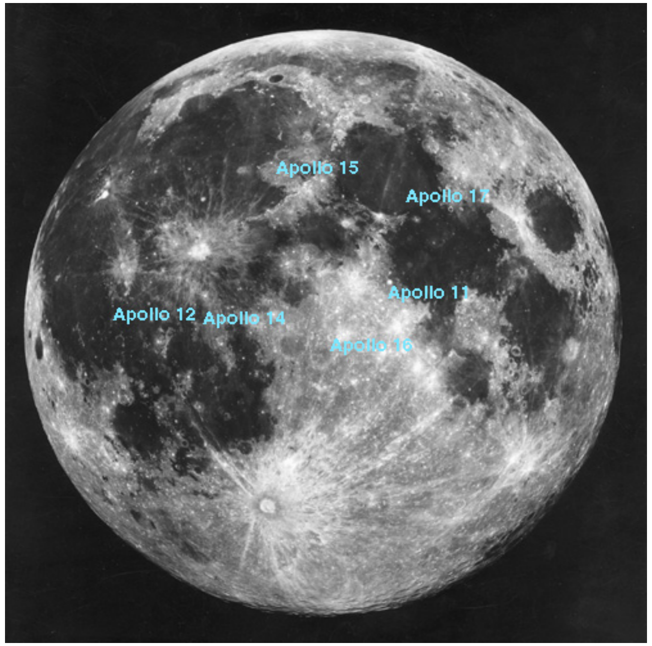


Lunar Exploration

- **Past Exploration**
  - 100+ robotic spacecraft missions
  - Only celestial body beyond Earth visited by Humans
    - Apollo missions (1969 – 1972)
      - Equatorial region
    - 12 Apollo Astronauts walked on the lunar surface
    - ~10 days on lunar surface / 80 hours outside of lander

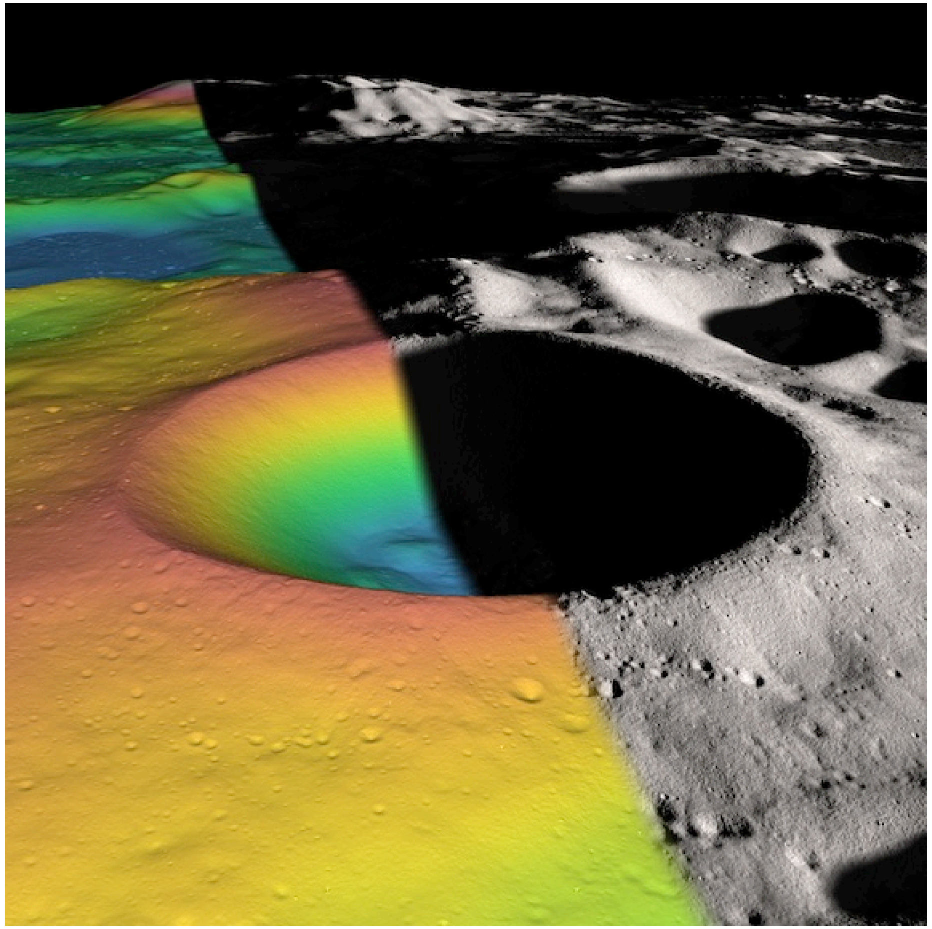


- **Future Human Missions**
  - Living beyond Earth
    - Testing and demonstrating technologies for sustained presence (Lunar and Mars)
      - 30+ day missions on the surface
  - Lunar South Pole
    - Polar Regions have limited temperature swings and more continuous sunlight
      - Minimizes energy storage
      - Contains volatiles



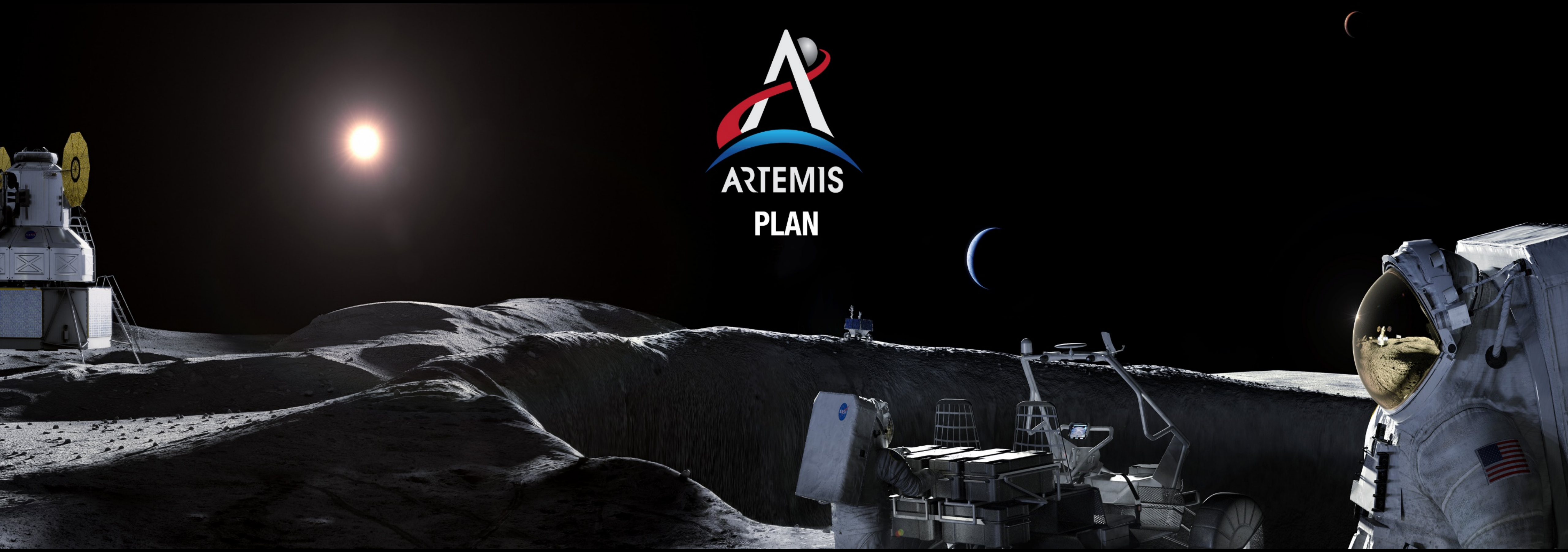
Shackleton Crater

- **Impact crater at the South Pole**
- **Named after Antarctic Explorer Ernest Shackleton**
- **Size:**
  - 21 km (13 mi) in diameter and 4.2 km (2.6 mi) deep
- **Rims are in almost continuous sunlight**
- **Interior is perpetually in shadow (eternal darkness)**
  - Average temperature -183 C (90 K)
  - Temperature never exceeds -173 ºC (100K / -280 ºF)
  - Any water vapor that arrived at the lunar surface from comets or meteorites would have been trapped



*Haruyama, Junichi; et al. "Lack of Exposed Ice Inside Lunar South Pole Shackleton Crater". *Science*. **322** (5903): 938–939. November 7, 2008

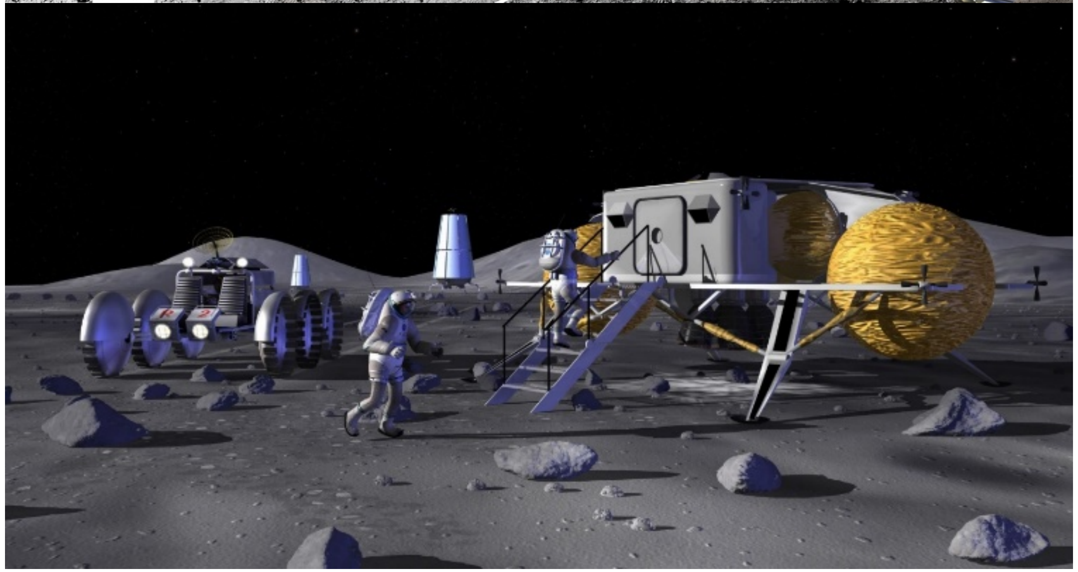
Sustainable Lunar Surface Power



Sustainable Presence Lunar Surface Activities

- **Living beyond Earth**
  - Testing and demonstrating technologies for sustained presence (Lunar and Mars)
- **Sustainable activities**
  - Manufacture propellant
    - Fuel landers for round trips between the Lunar surface and Gateway
      - Mining/excavation regolith
      - In-Situ Resource Utilization (ISRU)
  - Crew operations
    - 4 Astronauts for at least 30 days / four times per year
  - Lunar science and technology demonstrations

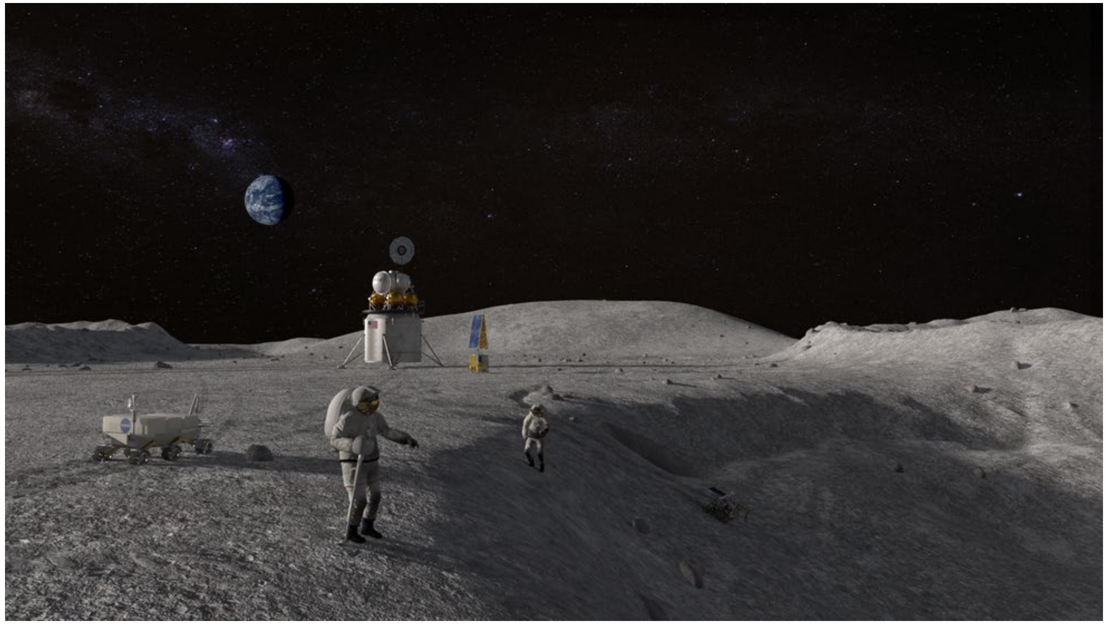
A sustainable Lunar presence requires highly reliable and available electrical power



Lunar Surface Sustainable Power Challenges

Lunar surface activities will grow and evolve over time

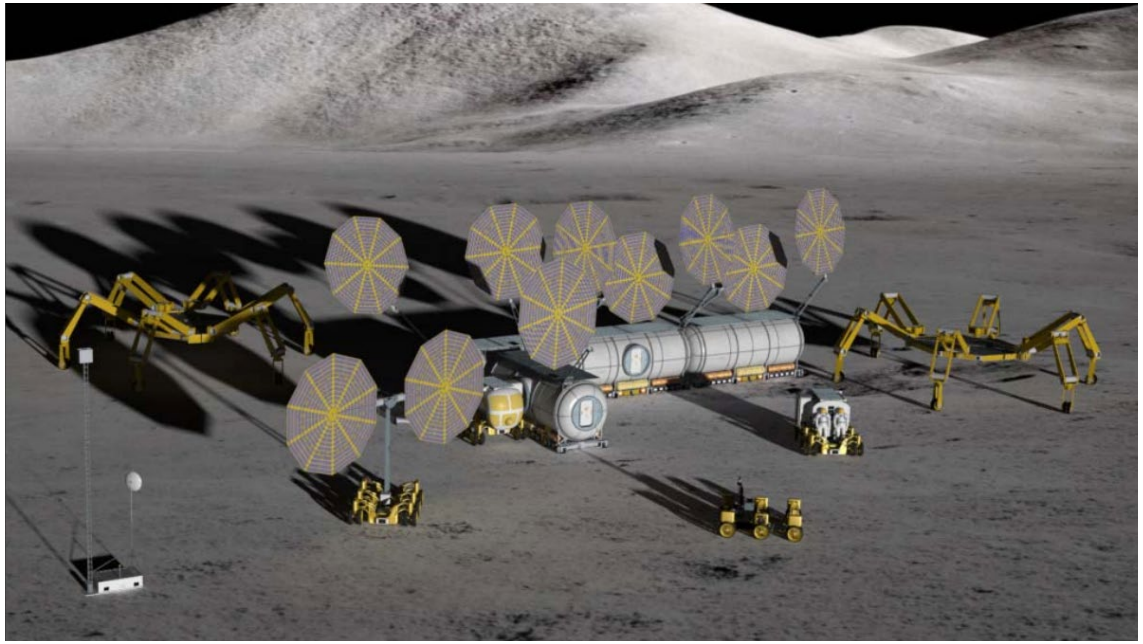
- **Power Architecture Challenges**
  - Complex power strategy (generation / storage)
    - Include dissimilar power sources
  - Distributed distribution architecture
    - Mix of generation, storage, and loads
- **Power Availability Challenges**
  - Peak power demand
  - Night-time power demand
    - Extend daylight operations
- **Operational Challenges**
  - Robotically deployable PMAD / power systems
  - Autonomously operated PMAD systems

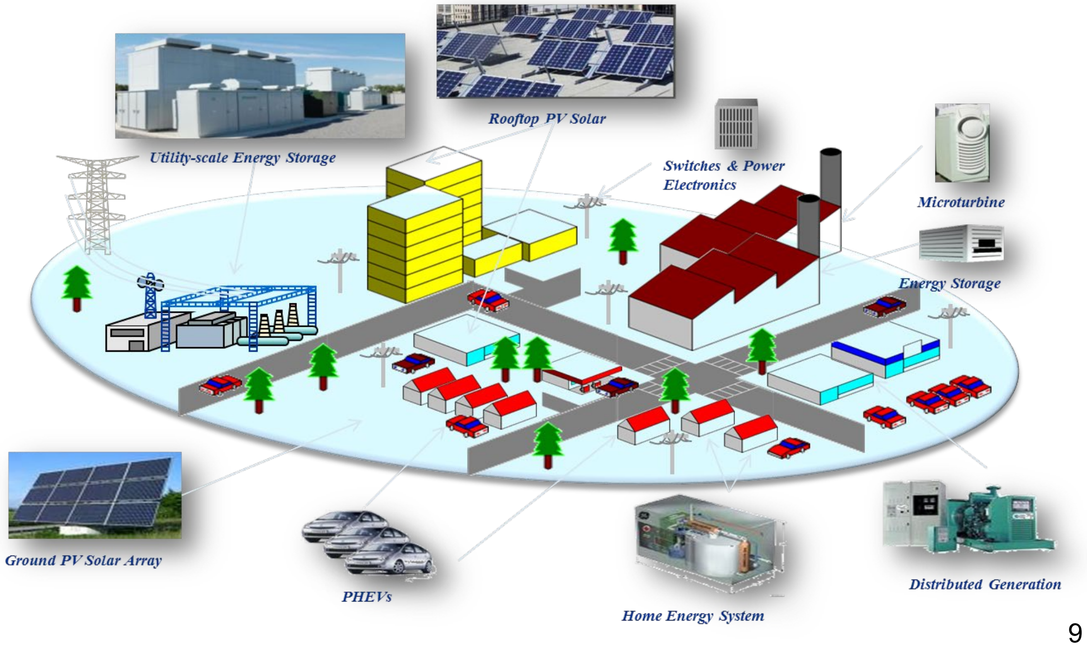


These are the same challenges/barriers for terrestrial based microgrids

Case for a Microgrid

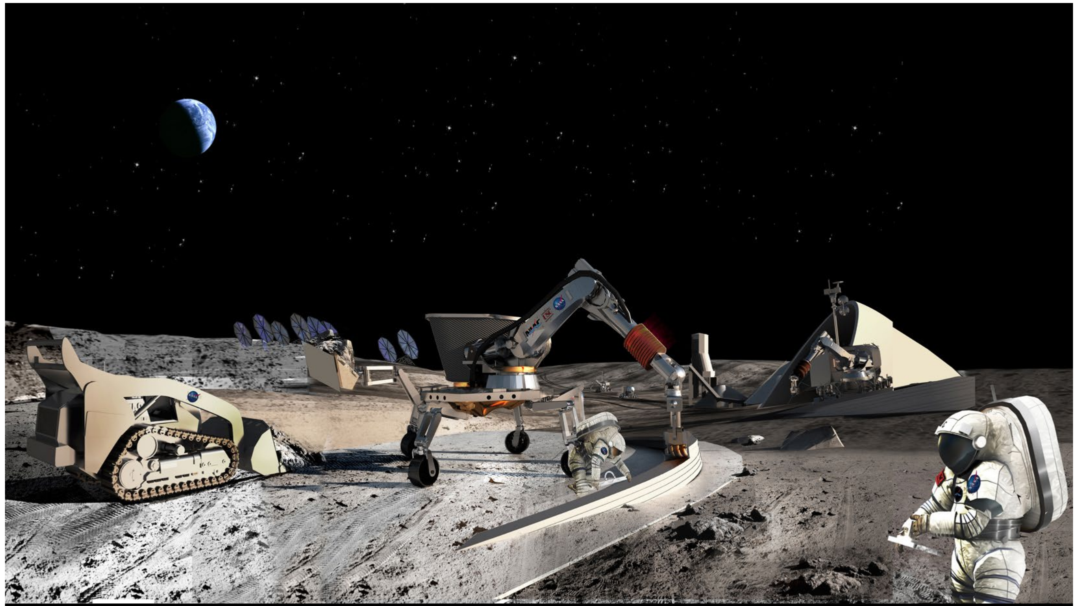
- **Lunar microgrid to provide electrical power**
  - Flexibility, evolvability, and reconfiguration
  - Optimal dispatch of power sources and energy storage to service loads & enhance reliability
  - Systematic integration of new sources and loads
  - Allow development and use of a common grid interface
  - **Allows for the deployment of future science loads that do not need to carry their own power generation**

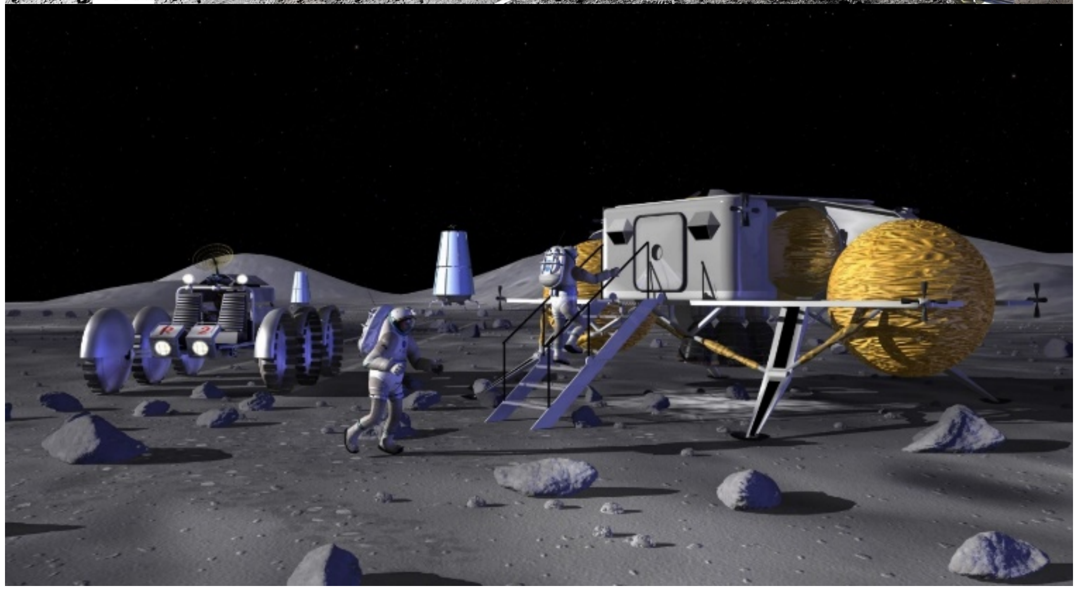




Lunar Surface Microgrid

Power Users

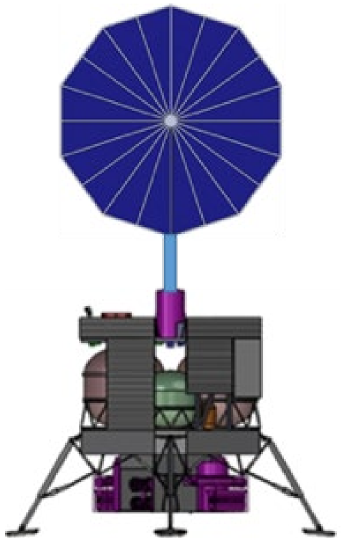




- **In-Situ Resource Utilization (ISRU)**
  - Largest power user 60+ kW
  - Power is needed over long distances
    - Mine water ice in crater, transport to crater rim, process into H_2, O_2
  - Restricted to operate during periods of heavy insolation
- **Habitat**
  - – Second larger power user during habitation
    - 20 – 50 kW
  - – Crew of 4 for 30+ days – 4 times per year
  - – Habitation restricted to periods of heavy insolation
- **Lunar science / Exploration**
  - – Various rovers @ 500 W each
  - – Power beaming @ TBD power

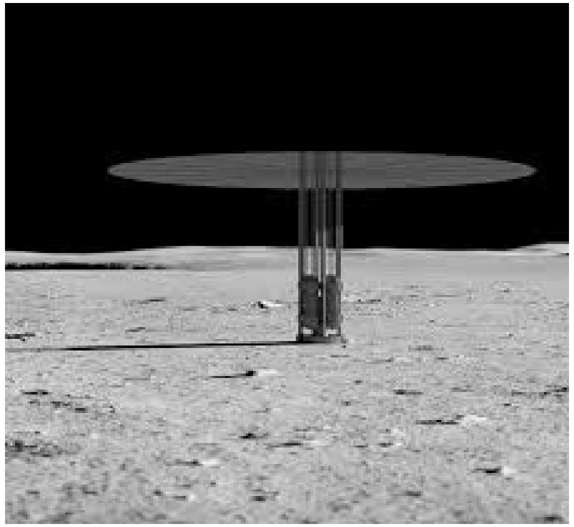
Power Generation & Energy Storage

Solar Arrays



Primary Fuel Cells

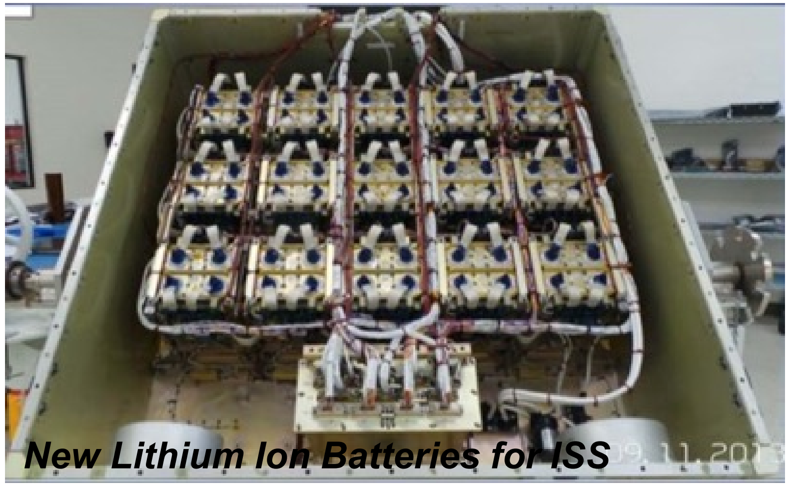
Radioisotopes (RTG, RPS, etc)



Fission Surface Power

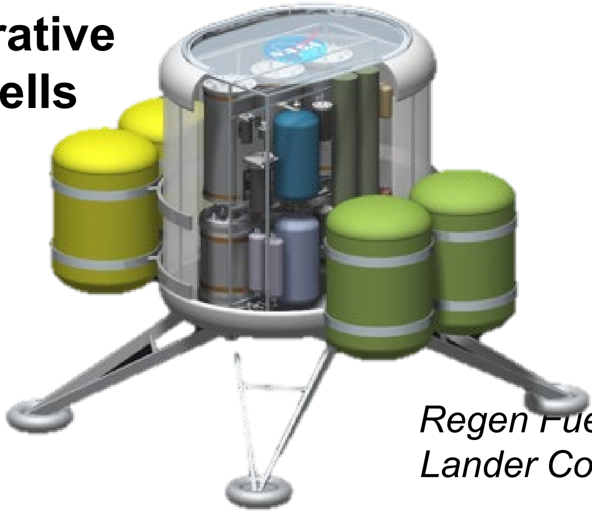
Tech Demo

Batteries



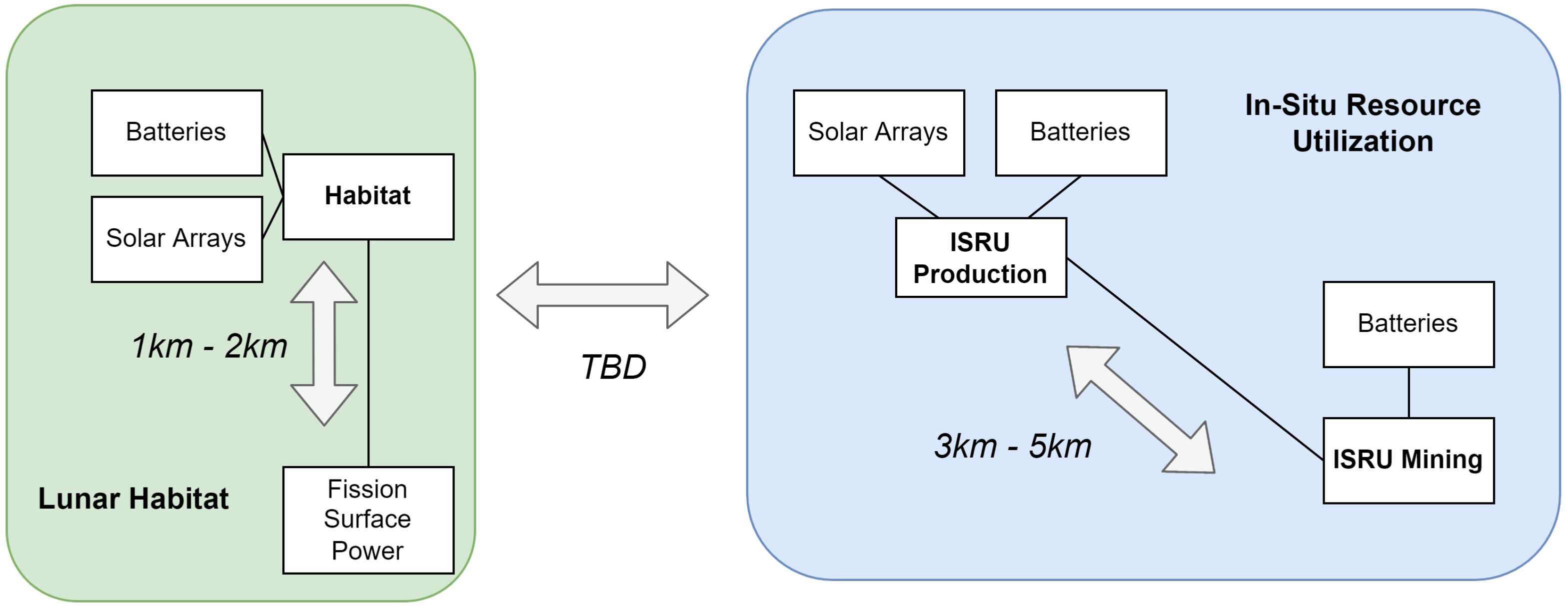
New Lithium Ion Batteries for ISS

Regenerative Fuel Cells



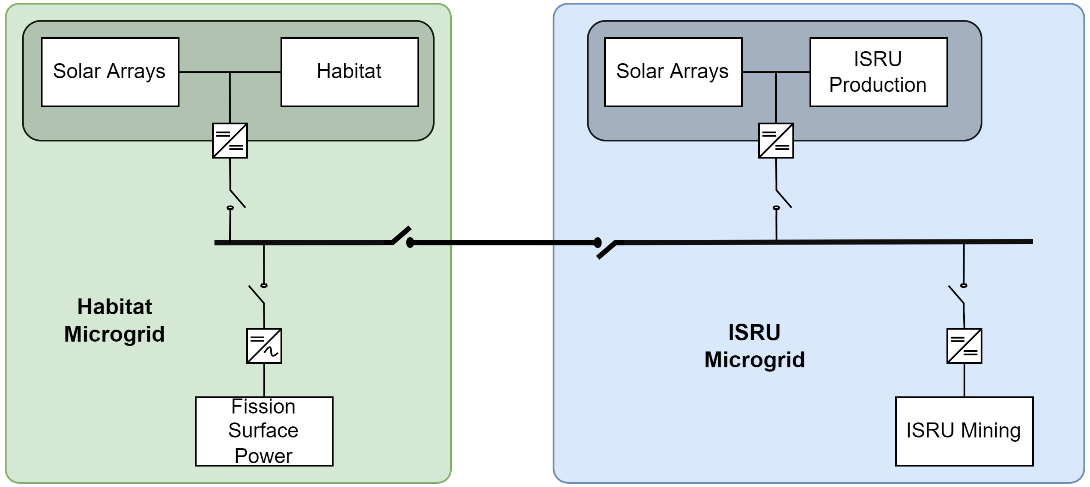
Regen Fuel Cell Lander Concept

Notional Artemis Lunar Base

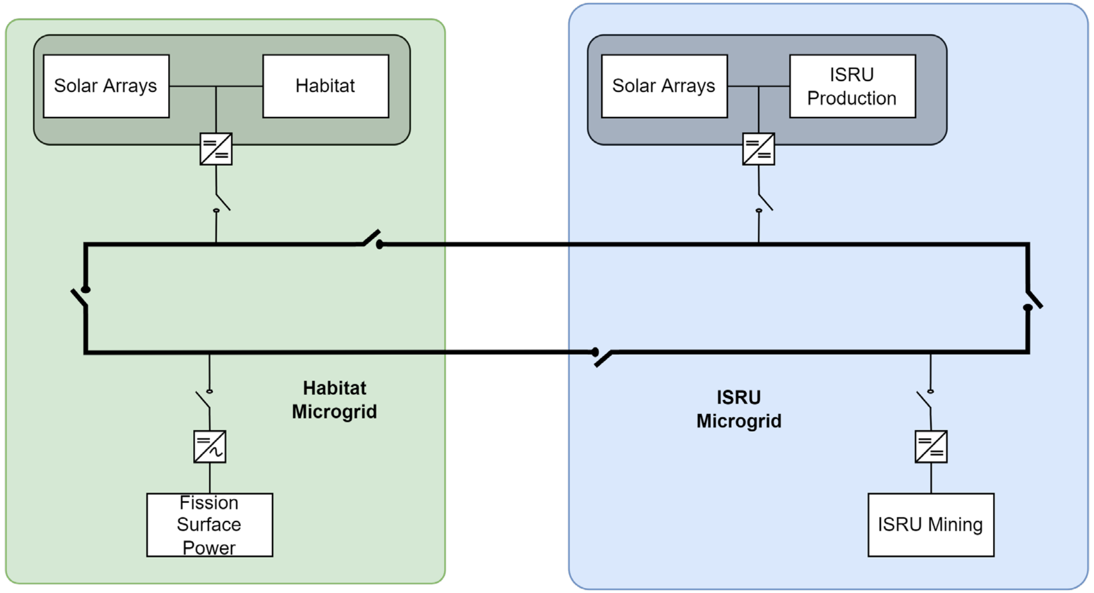


- **Major lunar power consumers have dedicated power sources and their own energy storage**
  - Consumers: Habitat and ISRU
  - Main Power Sources: Solar Arrays and Fission Surface Power
- **Can excess power be shared between sources and to other future power consumers?**
- **How can this be accomplished?**

Lunar Microgrid Architectures

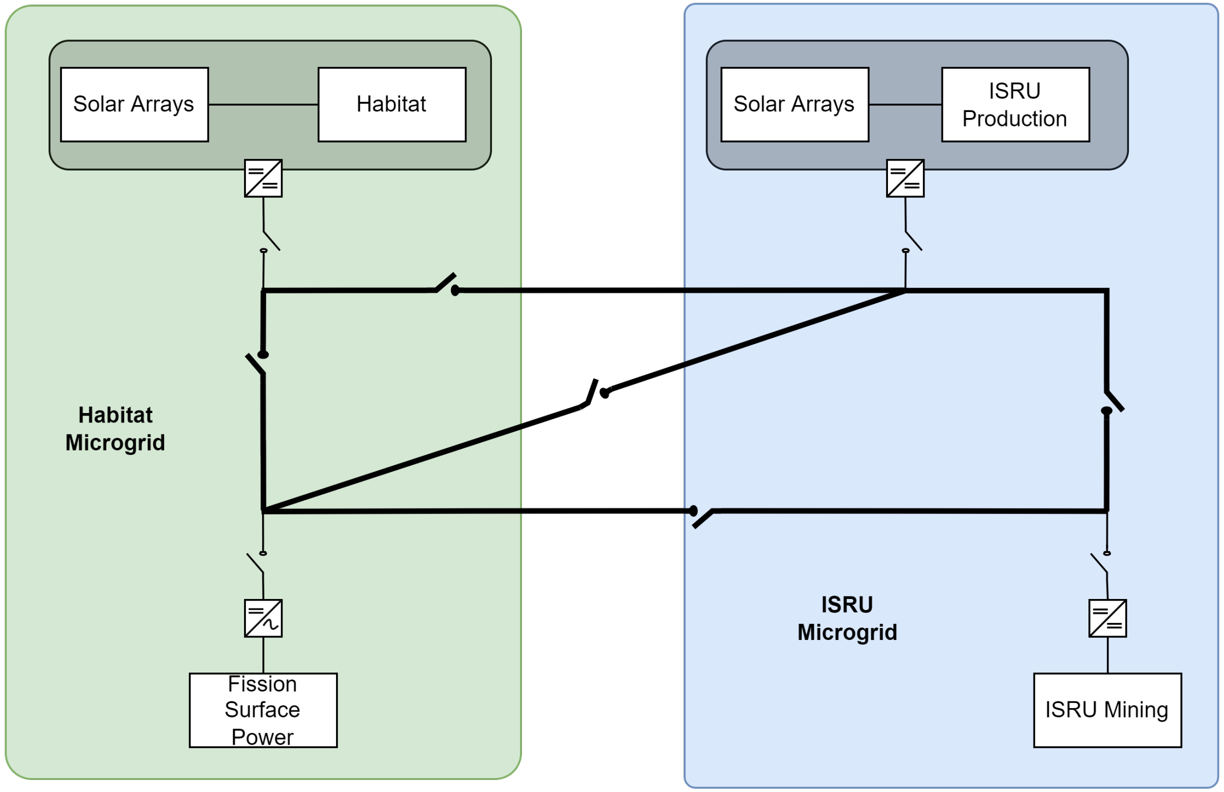


- **"Radial" Architecture**
  - Contains a single HV bus where all islanded microgrids share a connection
  - Simple and lowest implementation cost
  - Lack protection / redundancy during failure



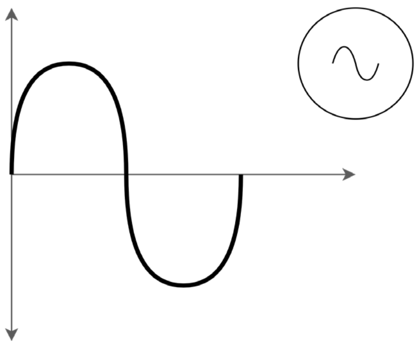
- **"Ring/Loop" Architecture**
  - Contains a HV bus that connects all devices and allows for power flow in either direction.
  - Increased redundancy since power can flow in either direction

Lunar Microgrid Architectures



- **Zonal Architecture**
  - Most reliable architecture
  - Allows for islanded operation under normal conditions
  - Allows for power sharing during off-nominal and faulted operation
    - Switches can be operated to create different architectures
    - Increased efficiency

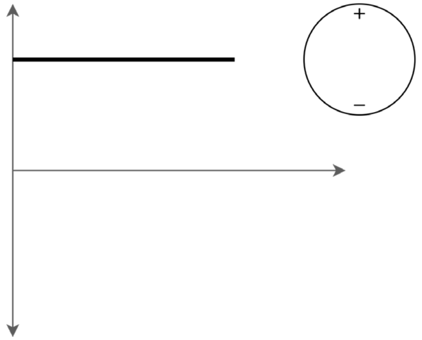
Power Transmission



AC vs DC

Alternating Current

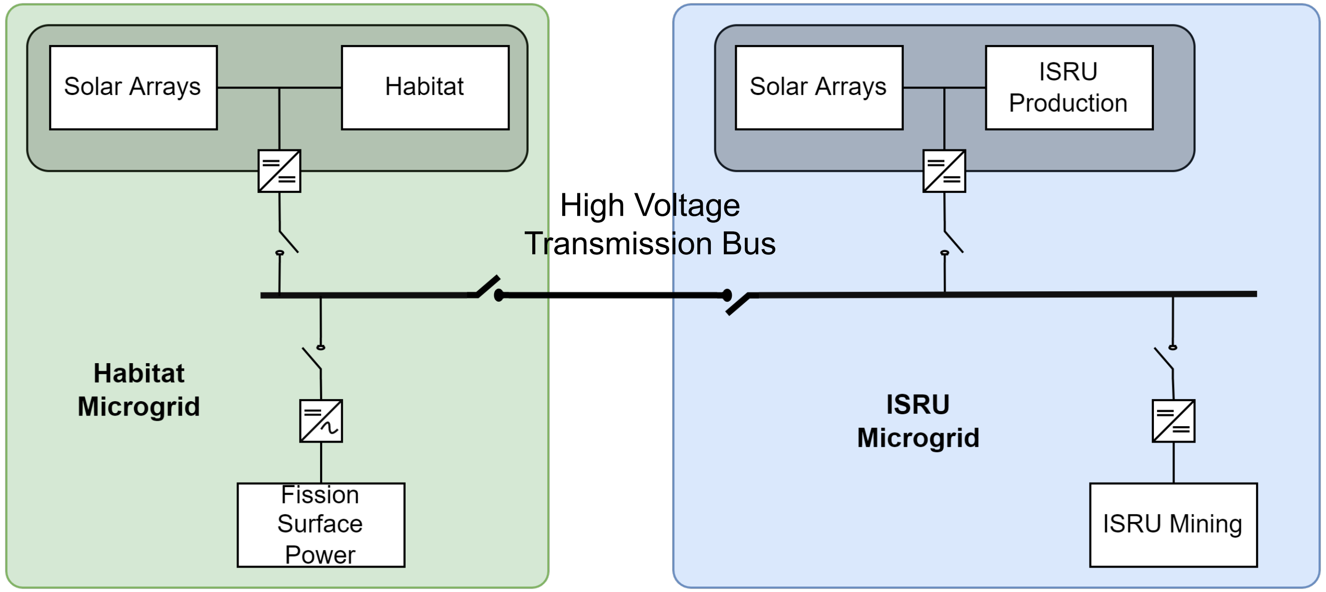
Direct Current



- **The War of the Currents**
  - Late 1880s between Thomas Edison (DC) and Nikola Tesla (AC)
  - DC is not easily converted to higher or lower voltages
- **Terrestrial Power Today**
  - Primarily AC
  - Increasing number of DC components
    - Computers, LEDs, solar arrays, electric vehicles are all DC
  - High Voltage DC
    - Growing interest due to efficiency, stability, and ability to connect asynchronous AC grids

Radial Architecture Trade Study

- **Initial studies focus on radial architecture**
  - Transmission bus voltage and power type allowed to vary (900 V and up)
  - Assume high voltage bus is near habitat, and primarily used to bring ISRU and AC source power to habitat, to serve as a backup
  - Assume AC source transmits three-phase power to habitat at 3 kV using a transformer, which avoids power electronics within AC source's radiation zone
  - Excess AC source power can flow to ISRU if habitat power needs are satisfied first



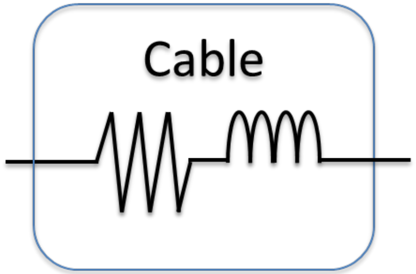
Note: For the small number of nodes that are in this system, a Star Configuration would look very similar, therefore we will not trade a star configuration in this set of trade studies.

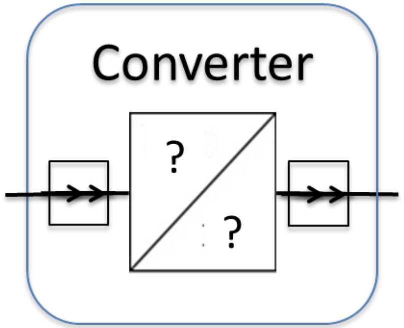
- **Radial Advantages**
  - Simple (lower implementation cost)
- **Radial Disadvantages**
  - Lack protection / redundancy during failure

Radial Architecture Trade Study - Assumptions

- **All transmission components sized for 40 kW to bus FSP power anywhere in grid**

- **Cables**
  - Copper 10-14 AWG wires with ETFE insulation (~90% design efficiency at 40 kW)
  - If individual wire cannot handle the line power, a bundle of parallel wires will be used
  - Skin/proximity effect, inductance, temperature modeled, others (e.g. regolith) ignored
- **Converters**
  - 95% efficient if DC-DC (bidirectional DC-DC)
  - 96.5% efficient if DC-AC (bidirectional inverter)
  - 98% efficient if AC-AC and no AC frequency changes (a transformer)
- **Loads/Sources**
  - Habitat includes 2x 10 kW sources (20 kW capacity)
  - ISRU includes 8x 10 kW sources (80 kW capacity for 68 kW load plus losses)
  - 40 kW FSP is the AC source, and is not used/present in islanded operating mode

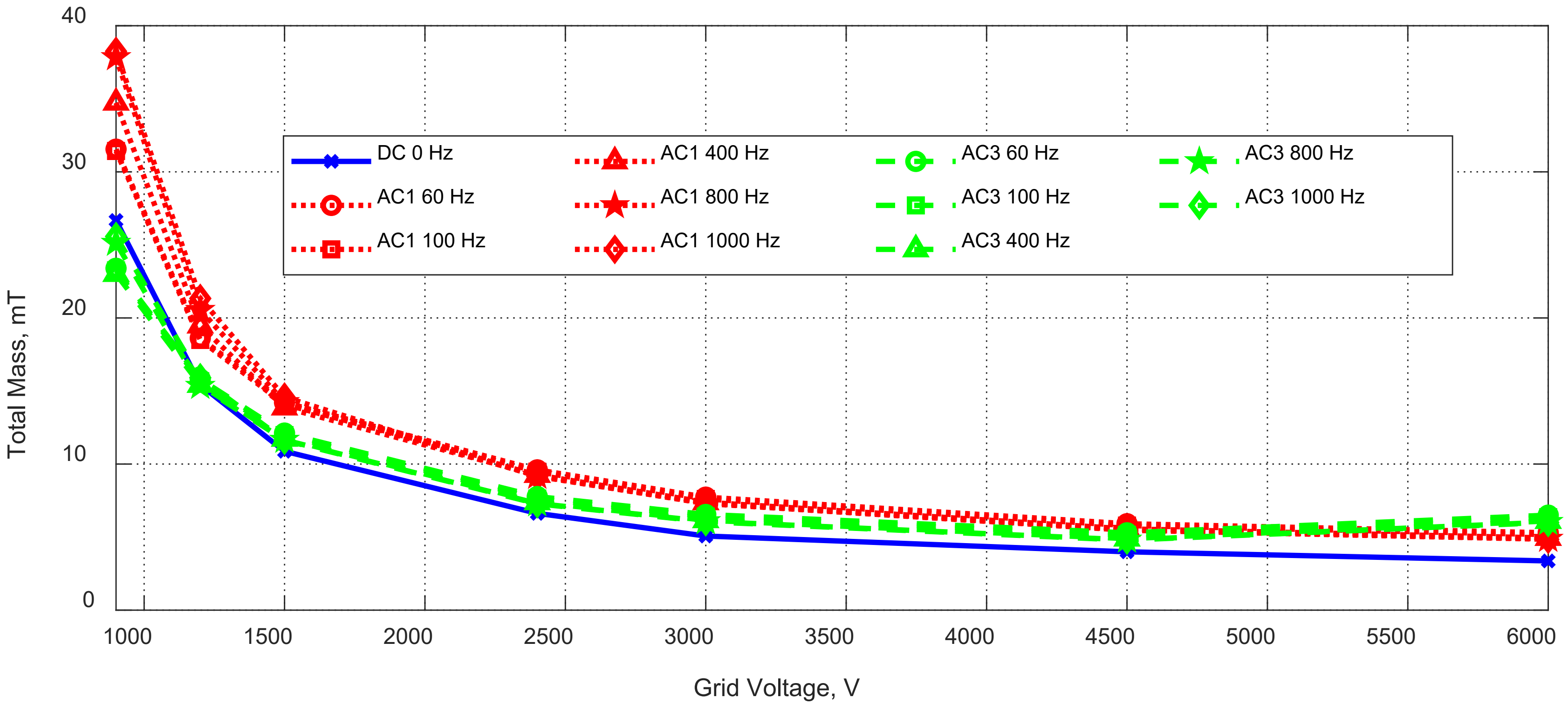




Radial Architecture Trade Study- Results

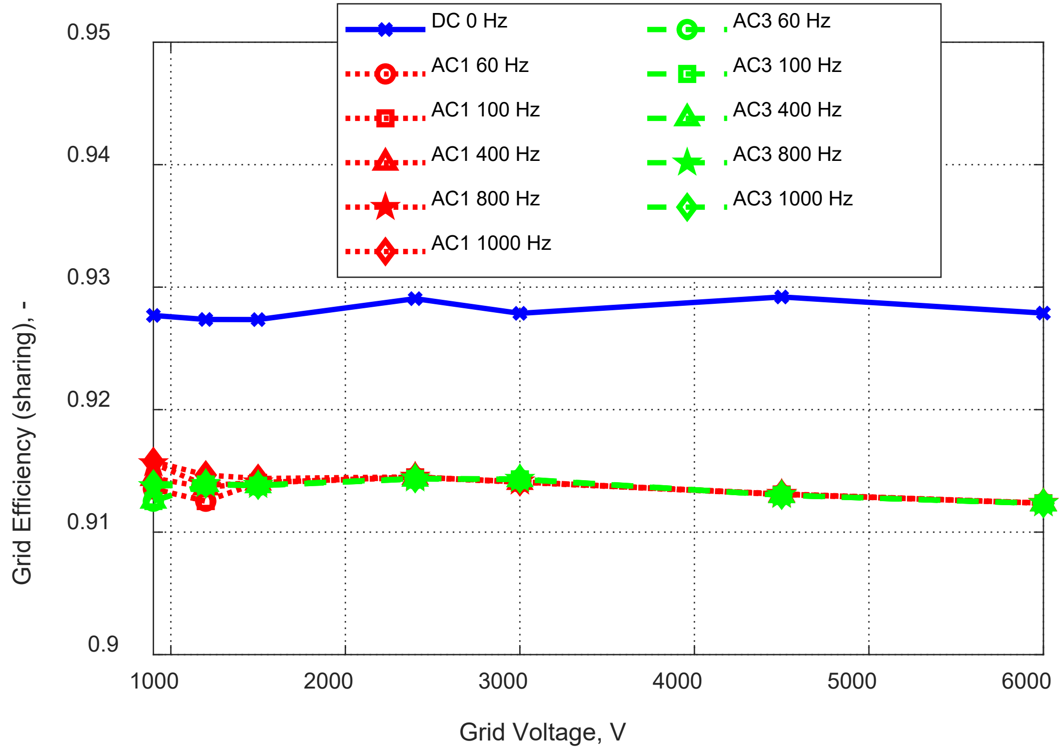
- **Showing total transmission mass (cables plus converters)**
  - Mass varies most significantly with voltage, power type does not strongly affect mass
  - If DC, select the highest voltage that is possible with a reasonable number of series converter stages
    - Best options may be 1200 or 1500 V
  - If AC, select the highest voltage that does not incur undue risks (corona, partial discharge, safety…)
    - Can go 3-6 kV, and pick frequency based on component availability/practical needs

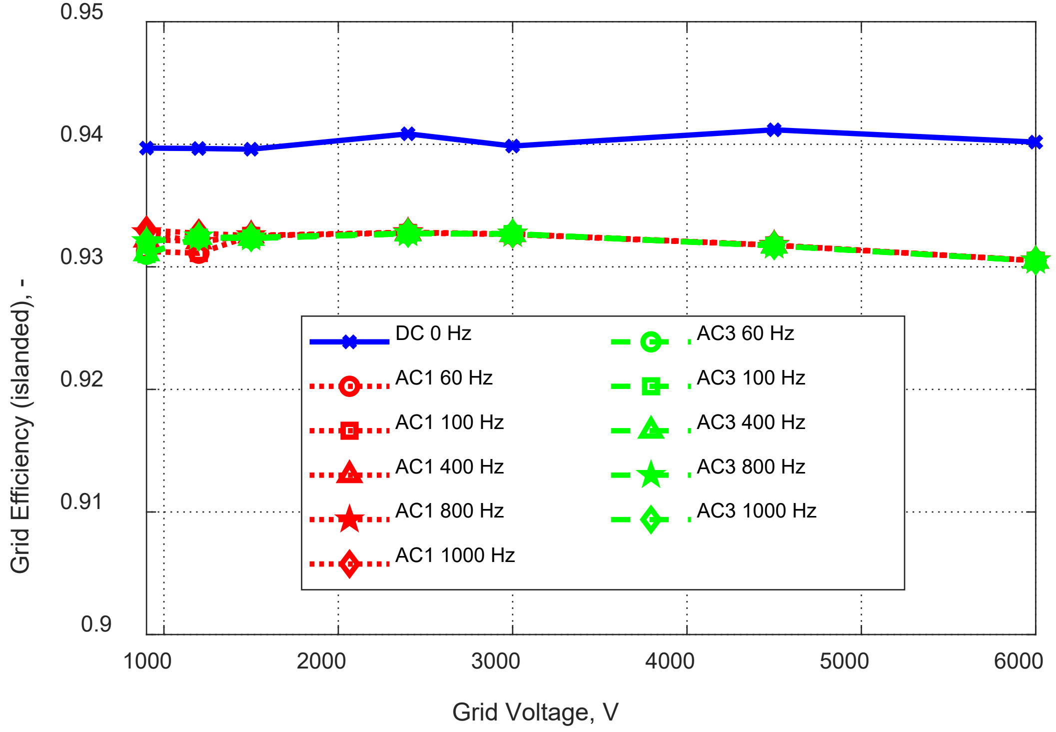
- **Single phase is heaviest option as to be expected**
  - Can be omitted from future trades
- **Three phase and DC mostly neck-and-neck, with DC slightly lighter at high voltages**



Radial Architecture Trade Study - Results

- **Grid designs chosen to hold efficiency approximately constant & let mass vary, but some differences**
  - AC converters assumed more efficient (96.5% or better vs 95% for DC-DC)
  - But DC/AC converters assumed to run at 0.98pf worst case, so AC overall efficiency slightly less
  - Islanded mode more efficient vs power sharing mode because most power consumed where it's produced

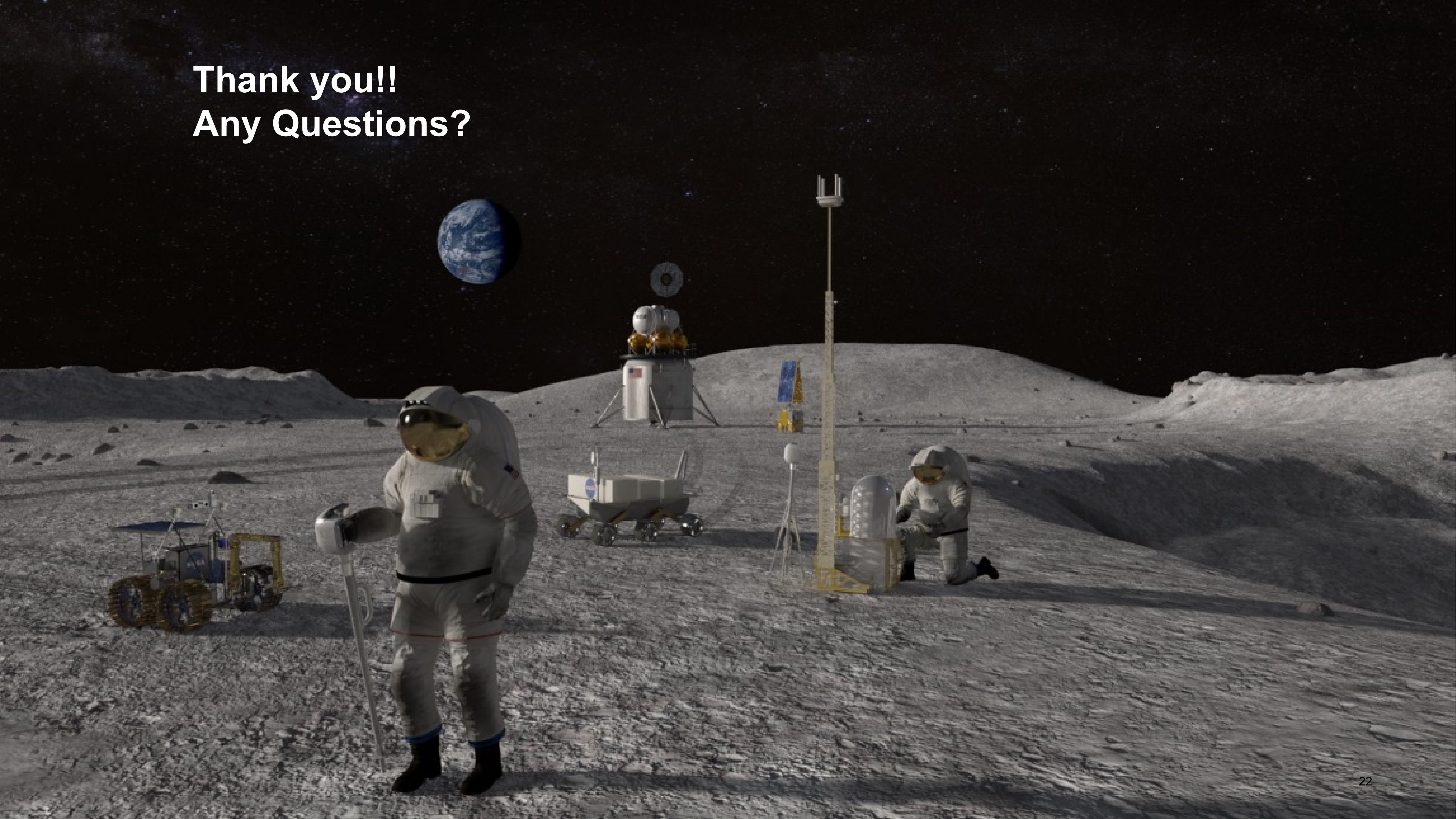




Summary

- **Lunar Surface Power**
  - Requires reconfigurable, highly available and reliable power to support a sustainable presence
    - Integration of dissimilar power sources
    - Autonomous operation
- **Rising interest in microgrid technology**
  - Space, Military and Terrestrial applications
    - Need for higher reliability, availability and reconfigurability
    - Desire for alternative (renewables) power sources (generation & storage)
  - Microgrids require complex operational scenario to achieve maximum benefit
    - Successfully integrate dissimilar or alternative power sources (interoperability)
    - Ability to reconfigure the system and switch between power sources quickly
    - Quickly detect faults/failures and reconfigure the system to avoid power disruptions
  - These complex scenarios are driving the need for autonomous power to deliver uninterrupted service regardless of application

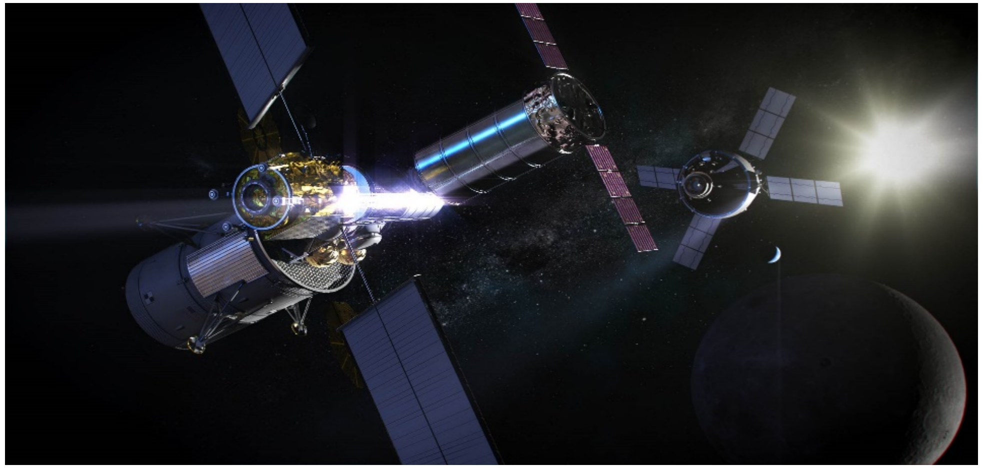
Thank you!!
Any Questions?

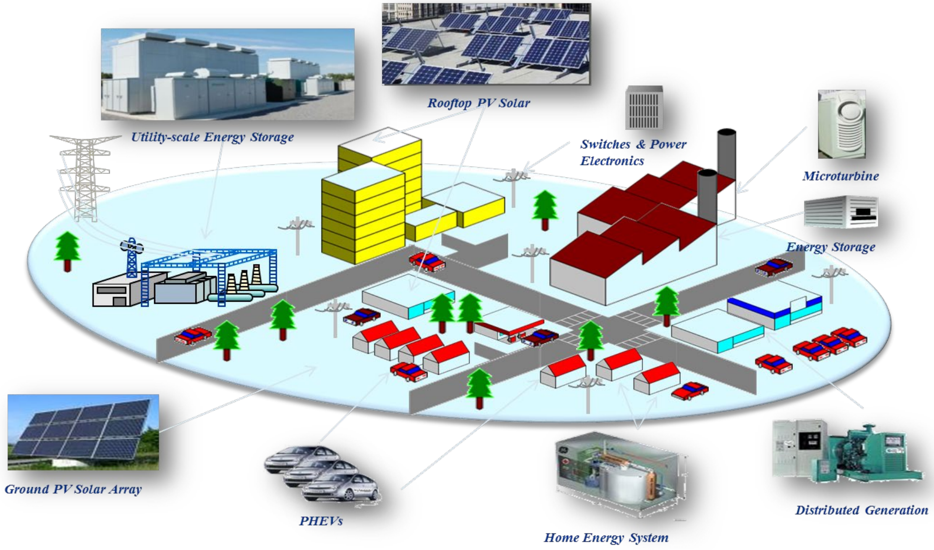


Autonomous Hierarchical Microgrid

Space Power Control

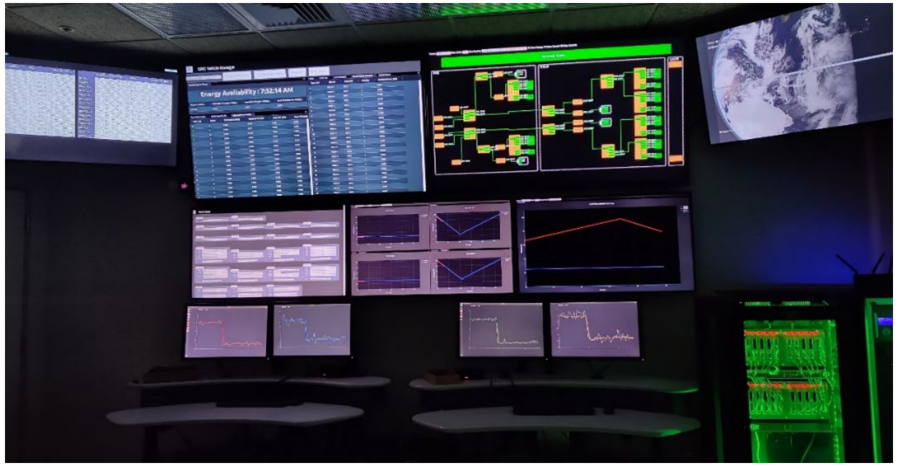
- **Power System Objectives**
  - Provide power to as many high priority loads as possible
  - Operate safely - within power system constraints
    - Power generation / energy storage constraints
    - Power distribution limits
- **Power Control Objectives**
  - Manage the power system
    - Energy Management
    - Fault Management
    - Contingency Management
- **NASA Autonomous Power Controller Objectives**
  - Manage the power system without human intervention
  - Permit humans (Astronauts) to consent to an operations /actions during habitation





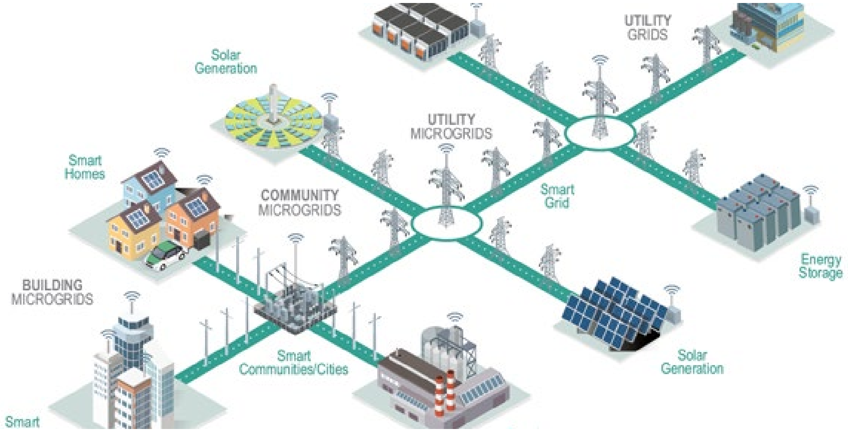
NASA Autonomous Power Controller

- **What is it?**
  - A collection of software services that interact to intelligently manage the power system without direct human intervention.



- **Why use it?**
  - Behaves like a grid operator control room packaged into software
  - Manages the grid during faults and disturbances
  - Designed for deep space exploration spacecraft but has direct applications to terrestrial microgrids

- **Key Capabilities:**
  - Energy forecasting and automatic load planning
  - Advanced fault detection and diagnostic engine
  - Contingency management
  - Distributed energy storage regulation

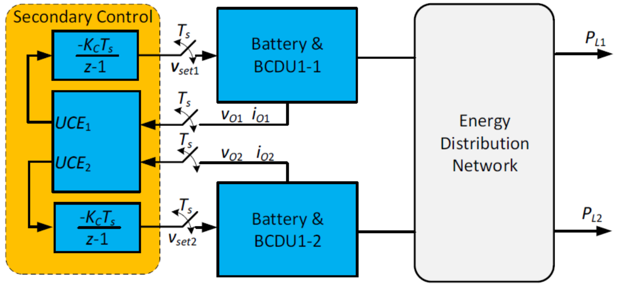


NASA Autonomous Power Controller Key Capabilities

Distributed Energy Storage Control

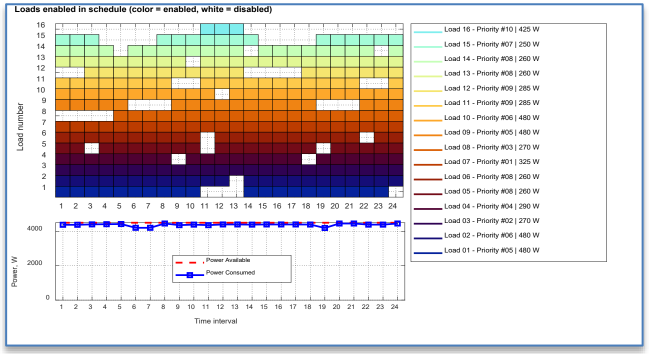
A three-level control pattern designed to:

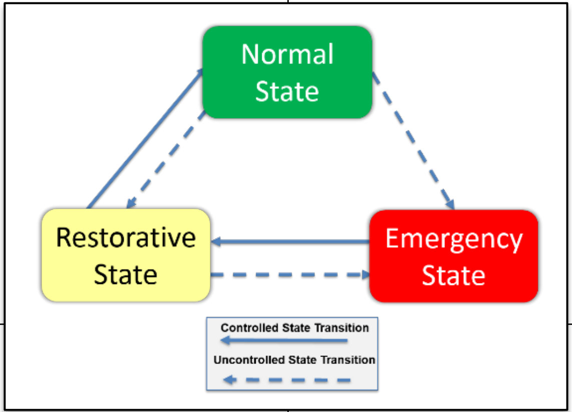
1. Regulate bus voltage
2. Provide even load sharing across DERs
3. Balance distributed storage SOC



Power Forecasting

Uses projected load and forecasted energy generation to simulate future operating conditions over a rolling time horizon. This allows system vetting before new operating conditions are implemented.

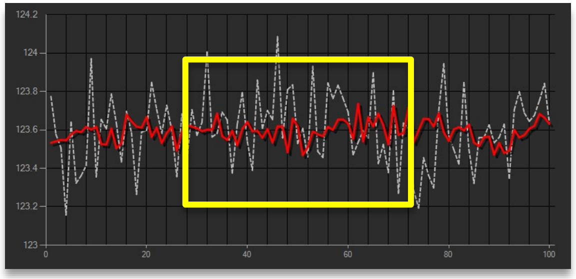




Fault Detection and Diagnosis

Combines modeling techniques with expert system to detect and diagnose a wide range of fault conditions such as:

line to ground faults,
high impedance shorts,
sensor faults,
communication faults, etc.



Contingency Management

Determines optimal corrective action in the event of an unexpected event or failure.

E.g. reconfigure topology during a line outage to balance energy storage